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# Return on Investment in Transmission Network Expansion Planning Considering Wind Generation Uncertainties Applying Non-Dominated Sorting Genetic Algorithm

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***Abstract***- *Although significant private investment is absorbed in different sectors of power systems, transmission sector is still suffering from appropriate private investment. This is because of the pricing policies of transmission services, tariffs, and especially for investment risks. Investment risks are due to the uncertain behaviour of power systems that discourage investors to invest in the transmission sectors. In uncertain environment of power systems, a proper method is needed to find investment attractive transmission lines with high investment return and low risk. Nowadays, wind power generation has a significant portion in total generation of most power systems. However, its uncontrollable and variable nature has turned it as a main source of uncertainty in power systems. Accordingly, the wind power generation can play a fundamental role in increasing investment risk in the transmission networks. In this paper, impact of this type of generation on investment risk and returned investment cost in transmission network is investigated. With different levels of wind power penetration, the recovered values of investment cost and risk cost in transmission network are calculated and compared. This is a simple method to find investment attractive lines in presence of uncertainties. Wherein, transmission network expansion planning (TNEP) is formulated as a multi-objective optimization problem with objectives of minimizing the investment cost, maximizing the recovered investment cost and network reliability. The point estimation method (PEM) is used to address wind speed variations at wind farms sites in the optimization problem, and the NSGA II algorithm is applied to determine the trade-off regions between the TNEP objective functions. The fuzzy satisfying method is used to decide about the final optimal plan. The proposed methodology is applied on the IEEE 24-bus RTS and simplified Iran 400 kV network.*

***Keyword:*** NSGA II algorithm, Point estimation method, Private investment, Transmission network expansion planning, Wind power generation.

## 1. INTRODUCTION

In the deregulated power industries, some new goals are pursued in TNEP. These goals are completely different from the traditional ones. For contradicting interests and non-commensurable goals, TNEP becomes a complex optimization problem in deregulated environment, and must be studied from different points of view. [1, 2]. One of these points of view is absorption of more private investment by the transmission section of the power system. In this regard, the private investors must be encouraged with more investment return and less investment risk. It is possible by applying an effective cost allocation methodologies to determine the merchant/ economic transmission lines for investing [3-5].

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Rahmani et al. [6] presented a risk/investment-driven approach to solve the TNEP problem considering multiple scenarios regarding future load and generation patterns. Trade-off between risk and investment is provided that enables the planner to determine the necessary investment for new transmission lines at a permissible risk level. Several market-based indices are presented in [7] in order to economic evaluation of candidate transmission expansion plans as well as selecting the optimal ones. After adding each candidate plan, change in social welfare is calculated and compared with the needed investment cost. Finally, the plan with the best cost-benefit balance is determined as the optimal plan. Reference [8] proposed a methodology based on the investment risk in order to facilitate implementation of a centralized transmission expansion plan when several investors compete and bid to build a new transmission asset. This methodology improves investors' optimal investment portfolios and allows a central planner to identify the optimal expansion plan. Reference [9] used a risk-based approach to achieve a robust and cost-effective expansion plan for transmission networks. The uncertainties of load, wind speed and power system components forced outage rates are addressed in the planning problem. The approach is decomposition-based in nature that the security and transient stability of power network is checked along with a long-term expansion planning. However, the transmission sector is still suffering from inappropriate private investing. This is because of the pricing policies of transmission services, tariffs, and especially existing investment risks. Investment risks are due to uncertain behavior of power systems that discourage investors to invest in the transmission sector [10-12].

In one hand, the power systems uncertainties discourage investors to invest in the transmission sector, and in the other hand, the deregulation and unbundling lead to more uncertainties in the power systems and intensify the existing ones [13-14]. So, private investment absorption in transmission sections is not compatible with these uncertainties. However, analyzing impacts of these uncertainties on the investment risk and determining the merchant transmission projects can be helpful. Also, a proper method is needed to determine private investment attractive lines with high investment return and low investment risk, in presence of power system uncertainties. This is the main aim of this research paper.

Among uncertainties, studying impact of uncertainties associated with power generation on the investment risk has a great importance; wind power generation has got a great attention in many power industries and it is estimated to have a notable portion in the future power production [15]. However, the uncontrollable and variable nature of this type of generation has turned it as a main source of the uncertainty in the power systems [16]. Accordingly, wind power generation can play a fundamental role in increasing investment risk in transmission networks. Impacts of the wind power penetration on the TNEP problem and its objective functions are frequently investigated in literatures [13,17-19]. In this paper, impact of wind power generation on investment risk and recovered investment cost in TNEP is investigated. To this end, with different levels of wind power penetration, the recovered values of investment cost in the transmission network are calculated and compared. In this regard, some of the conventional generation capacities at some buses are replaced by wind power type. Variations of wind speed at wind farms sites are modeled using the well-known Weibull probability distribution function (pdf) [20], and addressed in the optimization problem by the Point Estimation Method (PEM) [21]; PEM is a simple relatively-accurate technique to calculate the probabilistic power flow in the power systems [22-24]. Thereby, it can be seen how wind power penetration can reduce number of attractive lines and consequently change investors' motivation to invest in the transmission sector of the power systems.

As TNEP in the deregulated power systems is a multi-objective optimization problem, a posteriori approach with the ability of generating trade-off between different objective functions should be applied. These trades-offs enable transmission expansion planners to decide about the final plan with a better subjective judgment [1][2]. Some mathematical and evolutionary algorithms are proposed to find trade-off between the TNEP objective functions. The genetic based NSGA II algorithm [25, 26] is more frequent due to its simple implementation and inherent capability in determining the trade-off regions of multi-objective optimization problems in power system planning [10,13,27-28]. Accordingly, in this paper, this algorithm is applied to handle the multi-objective TNEP problem. Then, the final optimal solution is searched among the Pareto (non-dominated) solutions by the Fuzzy decision making method. Here, the pursued objectives in the optimization process are minimizing the investment cost, maximizing the recovered investment cost and network reliability. It should be mentioned that the minimization of the investment cost of the transmission lines reduces the tariffs of the transmission services and facilitates competition in a power market [1]. Also, a reliable transmission network plays an important role in the successful trade in the competitive electricity market [27-30]. The proposed methodology is applied to the IEEE 24-bus RTS and the simplified Iran 400 kV network.

The rest of this paper is organized as follows. In Section 2, the problem formulation is developed. The simulation results are presented in Section 3, and some concluded remarks are drawn in Section 4.

## 2. PROBLEM FORMULATION

Some necessary theoretical concepts, problem modeling, and solution methodology of the studied multi-objective TNEP problem are developed in the following.

### 2.1. Wind power generation modeling

Output power of a wind turbine generator mainly depends to the wind speed at the turbine location. The wind speed changes alternatively and consequently the generator output varies stochastically between zero to its rated output that leads to the fluctuations and uncertainties in the power flow. Based on the literature, the probabilistic distribution functions are a suitable tool to model the stochastic behavior of the wind speed. Here, the commonly used Weibull distribution is chosen for this purpose. For the uncertain variable $x$, the Weibull distribution is as follow [31]:

$$f(x) = \frac{\beta}{\beta^{\alpha}} x^{\beta-1} e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{1}$$

Where, $\alpha$ and $\beta$ are known as scale and shape variables determined using the statistical data of $x$ variations. For wind speed $v$, the output of each wind power generator is calculated based on its the power-speed curve [31]:

$$P_W = \begin{cases} 0 & 0 \le v \le v_{ci} \\ P_R\,(v - v_{ci})/(v_r - v_{ci}) & v_{ci} \le v \le v_r \\ P_R & v_r \le v \le v_{co} \\ 0 & v_{co} \le v \end{cases} \tag{2}$$

Where, $P_R$, $P_W$, $v_{ci}$, $v_r$ and $v_{co}$ are the rated and output power of wind power generators, cut-in, rated, and cut-out speeds of wind turbines, respectively.

### 2.2. Objective functions of the TNEP problem

In the deregulated power industries, various objectives are addressed in the TNEP problem. Here, the studied objectives are the minimization of the allocated investment cost, maximization of the investment cost recovery, and maximization of the transmission network reliability.

#### 2.2.1. Investment cost minimization

Conventionally, the first and main objective of TNEP problem is the minimization of the needed investment cost for the network expansion. In the new environments, minimizing the investment cost of the transmission lines reduces the tariffs of transmission services and facilitates competition for the power market participants [1]. The investment cost *IC* is minimized as:

$$Min\,IC = \sum_{ij \in \Omega_c} c_{ij} n_{ij} \tag{3}$$

Where, $IC$ is the total investment cost, $c_{ij}$ the cost of an added line and $n_{ij}$ is the number of added lines to the right-of-way of $ij$. $\Omega_c$ is the set of right-of-ways.

#### 2.2.2. *Maximization of the recovered investment cost*

Insufficient transmission capacity is a serious obstacle in providing the nondiscriminatory and competitive market conditions to the participants [32]. Incentives policies can encourage the private investors and attract their investments to build new lines and improve the transmission system capacity. These policies must encourage investors with the high rate of investment return and low level of risk [10]. Thus, to encourage the investors, the merchant/economic transmission lines (attractive lines) should be determined using a cost allocation methodology [3-5]. Thus, the recovered investment costs can be maximized by:

$$Max\,RIC = \sum_{l=1}^{L} RIC_l^{AL} \tag{4}$$

Where, $RIC$, $RIC_l^{AL}$ and $L$ are the total recovered investment cost by all attractive lines, the recovered investment cost by the attractive line $l$ and the set of attractive lines, respectively.

A cost allocation method is needed to determine a set of attractive lines. Up to now, different cost allocation methods are implemented by the electric utilities. Postage-stamp rate, contract path, MW-mile, and unused transmission capacity methods have more practical application among the others. The postage-stamp rate method does not require the power flow calculations. It is independent of the transmission distance and network configuration. The method is based on the assumption that the entire transmission system is used, regardless of the actual facilities that carry the transmission service. The contract path method is analogous to an embedded cost method that does not require the power flow calculations. This method restricts the transaction to a specified and artificial path which may differ dramatically from the contract paths. The MW-mile is a method based on the power flow that is also known as a line-by-line method. Because it considers the changes in the transmission flows and transmission line lengths in miles. This method does not consider the percentage of the use of the transmission line capacity. This drawback of MW-mile method is improved by the unused transmission capacity method wherein all transmission users are responsible to pay for both the actual capacity use and the unused transmission capacity. So, the transmission users are charged based on the percentage utilization of the facility capacity, and the rule of the transmission service cost in the MW-mile method for the transaction *t* is revised as [33]:

$$TC_t = \sum_{k=1}^{K} C_k \frac{|f_{t,k}|}{\bar{f}_k} \tag{5}$$

Where, $TC_t$ is the cost of transmission service for *t*th transaction, $\left|f_{t,k}\right|$ is the flow of $k$th line for $t$th transaction. $\bar{f}_k$ and $C_k$ are the maximum capacity and the cost of transmission service per MW for $k$th line, respectively. $K$ is the set of all lines.

Here, this method is used to allocate the transmission service cost of a new line and determine its ability in recovering the investment cost. Having the annual cost of transmission service for the line $l$ ($TC_l^n$), the annual revenue ($A_l^n$) from this line is calculated as:

$$A_l^n = \alpha TC_l^n \tag{6}$$

At each power transaction, the cost of transmission service of line $l$ ($TC_l^n$) equals to its power flow (MWh-mile) times to its transmission tariff ($/MWh-mile). Note that, $TC_l^n$ is calculated based on annual Load Duration Curve (LDC) of power system. The annual return $\alpha$ is the investor share in the earned revenue from the transmission service. So, the present worth of the total revenue from the installed line $l$ (the recovered investment cost by line $l$ $RIC_l$) can be calculated using Eq. (7):

$$RIC_l = \sum_{n=1}^{N} \frac{A_l^n}{(1+d)^n} + SC_l \tag{7}$$

Where, $SC_l$ is the present worth of salvage cost of $l$th line, $d$ and $N$ are discount rate and the time horizon, respectively. However, to determine the merchant/economic transmission lines (attractive lines) an appropriate economic analysis is needed. For this, a valued method is used and this is assumed that a transmission project is merchant if satisfy two criteria of the minimum rate of investment recovery ($MRIR$) and the desirable level of investment risk ($Risk_d$), as follows:

$$\frac{mean(RIC_l)}{IC_l} \geq MRIR \tag{8}$$

$$\frac{std(RIC_l)}{mean(RIC_l)} \leq Risk_d \tag{9}$$

Where, $mean$ and $std$ are the expected value and standard deviation from the expected value, respectively. Accordingly, the probabilistic distribution of the recovered investment costs by building the prospective lines must be determined. It is carried out by calculating the probabilistic OPF that considers the random behavior of the loads. In the next sections, more discussion about the probabilistic OPF (POPF) is presented.

### 2.2.3. *Maximization of the transmission network reliability*

The final objective function is the maximization of the transmission network reliability. A reliable transmission network plays an important role in a successful trade in the competitive electricity market. The presented publications on TNEP show that different reliability and security criteria can be inserted in the TNEP formulation. Here, an N-1 based probabilistic reliability analysis is used, in which 1) respect to the operational constraints, the power system must be able to withstand the loss of any transmission facility, 2) in the post-contingency situations, the sum of the interrupted load and curtailed wind power generation should be minimized. Hereby, the objective function related to the transmission network reliability is calculated as:

$$Min\ RI = \sum_{c\in\theta} P_c (IL^c + CWG^c) \tag{10}$$

Where, $RI$ denotes the reliability index, $IL^c$ and $CWG^c$ are interrupted load and curtailed wind power generation due to contingency c, respectively. $P_c$ is the occurrence probability of contingency c, and $\theta$ is the set of contingencies.

To determine the interrupted load and the curtailed wind power generation with each contingency, a market-based OPF is calculated. A one-sided bidding model is supposed for the power market where participants offer the incremental costs as the hourly cost function together with their maximum generation. The utility would minimize the Hourly Social Cost (HSC) as follows [27].

$$\underset{\boldsymbol{P}_g, \boldsymbol{IL}}{Min}\ HSC = \sum_{i=1}^{n_g} p_{g_i}(a_i p_{g_i} + b_i) + p_f \sum_{j=1}^{n_d} IL_j \tag{11}$$

Where, $p_f$ is the penalty factor of load interruption. The objective function of Eq. (11) is subject to hourly DC load flow constraints as the physical constraints of power network:

$$\boldsymbol{S}^T \boldsymbol{f} + \boldsymbol{P}_g = \boldsymbol{P}_d - \boldsymbol{P}_W - \boldsymbol{r} \tag{12a}$$

$$f_{ij} - B_{ij}(n_{ij}^0 + n_{ij})(\theta_i - \theta_j) = 0 \tag{12b}$$

$$\left|f_{ij}\right| \leq (n_{ij}^0 + n_{ij})\overline{f}_{ij} \tag{12c}$$

$$\underline{\boldsymbol{P}}_g \leq \boldsymbol{P}_g \leq \overline{\boldsymbol{P}}_g \tag{12d}$$

$$0 \leq \boldsymbol{r} \leq \boldsymbol{P}_d \tag{12e}$$

$$0 \leq n_{ij} \leq \bar{n}_{ij},\ \forall(i,j) \in \Omega_c \tag{12f}$$

Where, $\boldsymbol{S}$ is the node-branch incidence matrix, and $\boldsymbol{f}$, $\boldsymbol{P}_g$, $\boldsymbol{P}_d$, $\boldsymbol{P}_W$, $\boldsymbol{r}$ are the vectors of power flows, generated powers, supplied loads, wind power generations and curtailed loads, respectively. $f_{ij}$ is the power flow in the right-of-way $ij$. $B_{ij}$ and $\overline{f}_{ij}$ are susceptance, and power flow limit of a single line in the right-of-way $ij$. $\theta_i$ and $\theta_j$ are the voltage angles at buses $i$ and $j$. $n_{ij}^0$, $n_{ij}$ and $\overline{n}_{ij}$ are the number of existing lines, number of new lines and maximum number of added lines in the right-of-way $ij$. $\underline{\boldsymbol{P}}_g$ and $\overline{\boldsymbol{P}}_g$ are the vectors of lower and upper generation limits. All variables in (11) and (12) are hourly parameters except for the number of added lines that for the sake of simplicity the time index does not show.

Note that, according to the current operating policies, the wind power generation must be dispatched with priority. Thereupon, in the above formulation, the production of a wind power generator can be curtailed, only if the OPF problem is infeasible.

For a better CPU time, a contingency selection strategy is used in this reliability analysis. All contingencies are ranked based on the product of their occurrence probability and total value of the interrupted load and curtailed wind power generation. Contingencies in which the mentioned value is very small, are neglected.

### 2.3. Probabilistic OPF calculation

The POPF must be applied to deal with the stochastic behaviors of wind power generations to the output variables. The necessary output variables are recovered investment cost by each new line and the RI. The probabilistic distributions of recovered investment costs can be determined by POPF and Eqs. (5) - (7). Here, the expected value of RI can be calculated as (9); wherein $IL^c$ and $CWG^c$ are expected values of interrupted load and curtailed wind power generation determined by POPF. In the literature, several techniques such as simulation, analytical and approximation methods are proposed to calculate POPF. Computational burden is the major weakness for the simulation methods, and analytical methods need complex mathematical calculations. The approximation methods are simple and relatively-accurate that can make a compromise between the previous mentioned methods. The point estimation method (PEM) is proposed by Rosenblueth [21] and it is first used in [22] to calculate POPF, and is frequently used in TNEP literature [10,13,34]. Accordingly, the two-point estimation method (2-PEM) is used to obtain the probabilistic distributions of output variables from the input variables.

### 2.4. NSGA II optimization method

A posteriori approach should be applied to make the trade-off between different objectives of the TNEP problem in the deregulated environment. It should use the concept of the Pareto optimality; a solution is Pareto-optimal (non-dominated) that improves at least one objective function without degrading the other ones. Some mathematical and evolutionary algorithms are proposed to find the non-dominated solutions of a multi-objective optimization problem such as NSGA and the mixed integer programming. Among them, NSGA has shown a good capability and robustness in handling the non-convex and non-linear problems [25,26]. In this paper, the NSGA II algorithm is used to determine the trade-off between objectives of the considered TNEP problem. The algorithm starts with a random initial population that is sorted into a set of Pareto solutions called the Pareto fronts. The Pareto fronts are ranked by the help of the non-dominancy concept that the first front includes the individuals with the highest fitness value. The crowding distance is computed for each individual and the population diversity is measured by the average value of the crowding distances. The parents are selected based on their non-dominancy ranks and crowding distances to generate the off-spring population, using crossover, mutation, and selection operators for the next iteration. This procedure continues until the termination criterion is satisfied [25].

### 2.5. Fuzzy decision making

The trade-off between the TNEP objectives helps the decision maker to decide about the final optimal plan. The final solution should be selected based on the decision maker judgment. So, an appropriate method with the ability of the human thought modeling is needed. The Fuzzy satisfying method is a proper tool to achieve this aim due to its similarity to the human subjective reasoning. A strictly monotonically declining and the continuous membership function are assigned to each objective [35]. For each objective, a solution takes a value from 0 to 1 from the membership function. This value determines the decision maker satisfaction about an objective. In this paper, the linear membership function is as follows.

$$\mu_{f_i}(x) = \begin{cases} 0 & f_i(\mathrm{x}) > f_i^{\max} \\ (f_i^{\max} - f_i(x)) \big/ (f_i^{\max} - f_i^{\min}) & f_i^{\min} \le f_i(\mathrm{x}) \le f_i^{\max} \\ 1 & f_i^{\min} < f_i(\mathrm{x}) \end{cases} \tag{13}$$

Where, $\mu_{f_i}$ is the membership function value for the

$i$th objective function. $f_i^{max}$ and $f_i^{min}$ are the maximum and minimum values for the $i$th objective function, and $f_i(\mathrm{x})$ is the value of this objective function for solution $x$. Based on the decision maker judgment, the satisfaction (desired) level of each objective is determined. Solving optimization problem of Eq. (13), the final solution will be found. This formulation would minimize the total deviations from desired levels.

$$\underset{x\in\varphi}{Min} \sum_{i=1}^{3} \left|\mu_{d_i} - \mu_{f_i}(x)\right|^{\rho} \tag{14}$$

Where $1 \le \rho < \infty$ . $\mu_{d_i}$ is the satisfaction level of $i$th objective, and $\varphi$ is the set of solutions. This formulation would minimize the $p$-norm deviations from satisfaction levels. The trade-off between objectives derived by NSGA II can help the decision maker to select reasonable satisfaction levels.

### 2.6. Implemented algorithm

The algorithm of Fig. 1 is implemented to solve the multi-objective TNEP problem. The algorithm starts with loading input data. The first population is initialized and objective functions are determined for each individual of the population. The investment cost ( $IC$ ) for each individual (each transmission plan) is calculated using (3). Adding each plan to the transmission network, the values of $RI$ and $RIC$ are determined. $RI$ is calculated using Eqs. (10) - (12). The $RIC$ value is determined by calculating POPF and Eqs. (4) - (9). The POPF is performed in no-contingency status (normal condition) to obtain probabilistic distribution of lines flow. For each new line, the cost transmission service cost, the annual revenue and the present worth of total revenue (i.e. recovered investment cost) are calculated from Eqs. (5) - (7). Considering probabilistic distribution of $RIC$ for each line, the satisfaction of minimum rate of investment recovery and desirable level of investment risk criteria are checked using Eqs. (8) and (9), respectively. It determines whether a built prospective line is attractive (merchant) for private investors or not. Having the set of attractive lines, the $RIC$ value for each individual of the population is calculated using Eq. (5). After determining the objective functions for all individuals, the population is sorted with respect to the objective functions based on the non-dominancy concept and the crowding distance is calculated for each individual. The parents are selected based on their non-dominancy ranks and crowding distances. The off-spring population is generated using the crossover, mutation, and selection operators, for the next generation. This process continues for the next generations until the termination criterion (the number of iterations) is met. If the termination criterion is met, the non-dominated individuals will be provided as the trade-off between the TNEP objectives. Finally, the decision maker decides about the final optimal plan based on his/her preferences using the Fuzzy satisfying method.

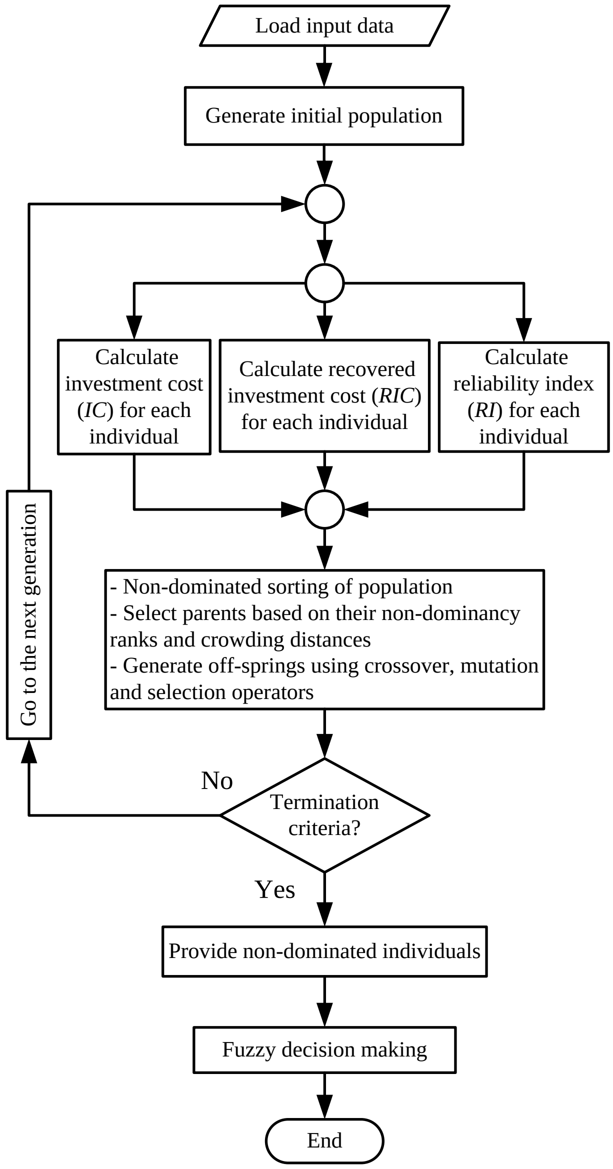



Fig. 1. The implemented algorithm.

## 3. CASE STUDIES

Simulations are carried out in the MATLAB environment with Matpower_Version 5.1 operation functions [36]. The IEEE 24-bus reliability test system (RTS) [32,37], and the simplified Iran 400 kV transmission network [27,38] are used as case studies. The single-line diagrams of these systems are presented in Appendices A and B. To calculate the objective functions, the relevant annual Load Duration Cure (LDC) is used; at each year of time horizon, objective functions are calculated based on minimum and maximum values of system load, and approximated for the other load levels based on the LDCs.

### 3.1. IEEE 24-bus reliability test system (RTS)

This system has existing 34 and new 7 right-of-ways for new transmission line installation. Let us assume, the network must be expanded for the next fifteen years, with the annual incremental rates of load and generation equal to 8% and 7%, respectively. The values of minimum rate of investment recovery ( $MRIR$ ), desirable level of investment risk ( $Risk_d$ ), annual return ( $\alpha$ ) and discount rate ( $d$ ) are 90%, 10%, 30%, and 10%, respectively. Based on the literatures [17,34], the generation buses 2, 7 and 22 are selected to install wind power capacity. Parameters of wind turbines and wind speed at these buses are similar to Manjil wind farm parameters, that $v_{ci} = 3.5$ , $v_r = 16$ , $v_{co} = 25$ , $\alpha = 13.8303$ and $\beta = 1.5081$ m/s [39]. The conventional generation capacities at these buses are 192, 300, and 300 MW at the first year, respectively. In order to study the impacts of the wind power generation uncertainty, some of the conventional capacities at these buses are replaced by the wind power type. For each percentage of the conventional capacity replacement, the algorithm of Fig. 1 is implemented to solve the considered TNEP problem.

Initially, the problem is solved without wind power generation. In this condition, the TNEP problem is deterministic. The determined trade-offs among objective functions of the TNEP problem are presented in Fig. 2. Fig. 2(a) is a trade-off between the investment and recovered investment costs. It shows that there is an incremental and supportive relation between the investment cost and the recovered investment cost. In the lower values of the investment cost, the transmission network has more potential to recover the invested cost; the number of new installed lines is fewer and the transmission network is more congested and utilized, and consequently more revenue from the new lines is earned to return the investment cost. However, for investment cost of 16 M$ and more, the supportive relation between the investment cost and recovered investment cost comes to a saturation mode. Note that, the excess installation of the new lines with their low utilization reduces the value of the recovered investment cost.

The trade-off between investment cost and the reliability index is given in Fig. 2(b). It illustrates that reliability of the transmission network increases as much as the increase in the investment cost. Because, an investment cost increment improves the transmission capacity and consequently improves the network reliability. It shows that with about 7 M$ of the investment cost, the reliability index becomes negligible.

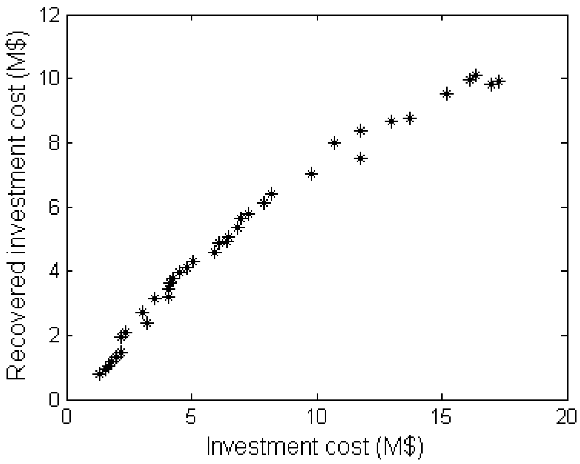
Now, two other simulations are separately performed; one with 40% and another with 80% of conventional capacity replacement at the buses 2, 7 and 22 by wind power type. For comparison, the obtained results along with the previous ones are shown in Fig. 3 in a collective manner. Hereby, the impact of wind power generation uncertainty on the TNEP objective can be analyzed better, especially on the recovered investment cost. Fig. 3(a) shows that in the deterministic condition (without wind power generation), the recovered investment cost is more than other cases. In this condition, the maximum recovered investment cost is M$10. While, this value is M$8 and M$6.2 for 40% and 80% of conventional capacity replacement by wind power capacity, respectively. For more analysis, suppose that investment cost is M$10.75; in deterministic condition, M$7.98 (74%) of it is recovered. While, M$6.47 (60%) / M$5.67 (53%) of this investment cost will be recovered, when 40% / 80% of the conventional capacity be replaced. Also, in deterministic condition, the relation between investment cost and recovered investment cost reaches to the saturation mode at the investment cost of M$16 and more. But, this saturation mode appears at about M$13 and M$11.5 of investment cost for 40% and 80% of conventional capacity replacement, respectively. This is because of the fact that the stochastic behavior of wind power generation increases the uncertainty level and investment risk, and consequently the remainder new transmission projects becomes non-attractive; the remainder new transmission lines cannot satisfy one or both of the criteria of the minimum rate of investment recovery ( $MRIR$ ) and the desirable level of investment risk ( $Risk_d$ ), i.e. the criteria Eqs. (8) and (9).

Figure 3(b) presents the trade-offs between the investment cost and the reliability index. It shows that with replacing the conventional capacity by the wind power type, the reliability index increases. Consequently, more investment cost is needed to reduce RI and improve the network reliability. Because, wind power generation decreases when wind speed reduces and there is not enough generation to supply loads near the wind power generators.

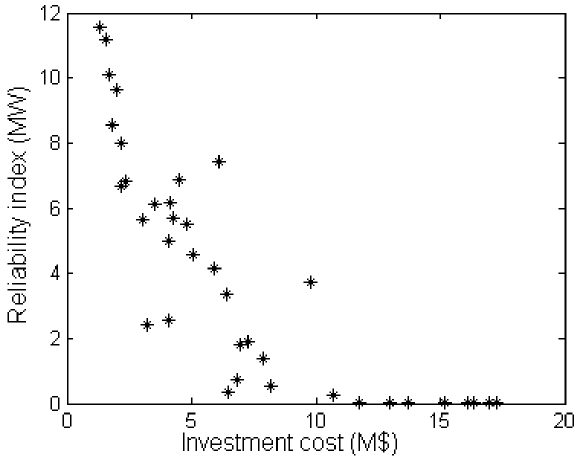
The decision making results from the Fuzzy satisfying method are presented in Tables 1 and 2. Table 1 presents results for each level of uncertainty with different satisfaction levels of TNEP objective functions. For the satisfaction levels, $\mu_{d_1} = 0.5$ , $\mu_{d_2} = 1$ and $\mu_{d_3} = 1$ , final plans are as Table 2. From Table 2, in the deterministic condition, there are more investment attractive line. These lines are selected as the final plan to expand transmission network. Hereby, the number of selected attractive lines is 9, 7 and 5 for 0%, 40%, and 80% of conventional capacity replacement, respectively. It is because of the fact that some lines cannot satisfy one or both of $MRIR$ and $Risk_d$ criteria. For example, the new line 8-9 satisfies these criteria and is selected as an attractive line for 0% and 40% of conventional capacity replacement. However, this line cannot satisfy the $Risk_d$ criterion when conventional capacity replacement is 80%, so is not an attractive line for investing. Also, the line 15-21 is selected as attractive in deterministic condition, but due to its inability in satisfying the $MRIR$ criterion is not selected for the two other states.

### 3.2. Simplified Iran 400 kV network

The simplified Iran 400 kV network has 76 existing transmission lines and 25 new right-of-ways to install new lines. As shown in Appendix B, there are 48 400/230kV substations and 4 new substations in this system. The solid lines/circles correspond to the existing right-of-ways/substations and dashed lines or circles are new right-of-ways/substations. The purpose is to expand this network for the next fifteen years with annual incremental rate of 5% for load and generation. These data are based on TAVANIR's plans [38], as the owner and planner of the Iranian EHV network. The three main wind farms in the Iran network are Manjil, Kahak and Binaloud. These farms inject their power to buses 6, 25 and 18, respectively. The relevant wind turbines data are

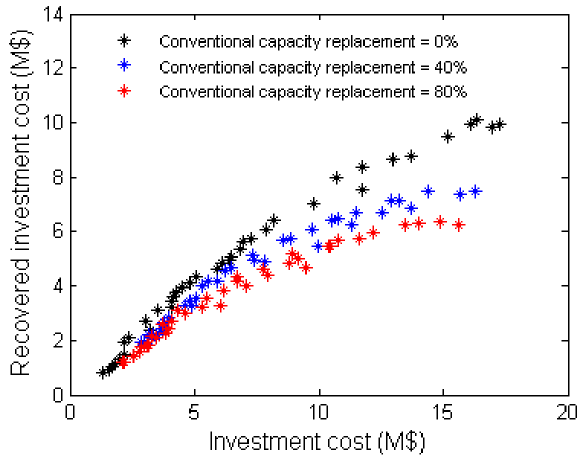



(a) Trade-off between investment cost and recovered investment cost.

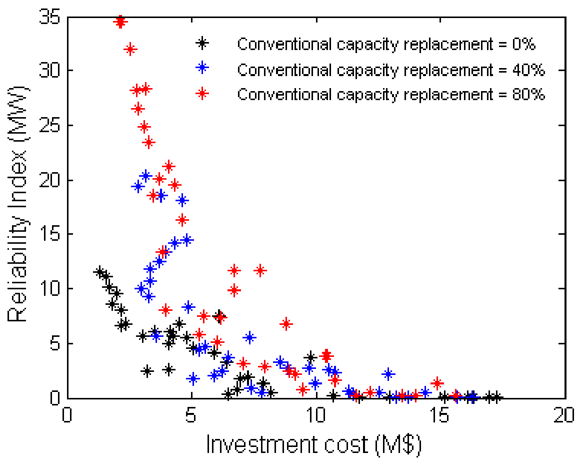



(b) Trade-off between investment cost and reliability index.

Fig. 2. Trade-offs between the TNEP objective functions in IEEE 24-bus test system, conventional capacity replacement = 0%.




(a) Trade-off between investment cost and recovered investment cost.




(b) Trade-off between investment cost and reliability index.

Fig. 3. Trade-offs between the TNEP objective functions in IEEE 24-bus test system, different percentages of conventional capacity replacement.

Table 1. Decision making by Fuzzy satisfying method.

| Satisfaction levels | | | Conventional capacity replacement = 0% | | | Conventional capacity replacement = 40% | | | Conventional capacity replacement = 80% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\mu_{d_1}$ | $\mu_{d_2}$ | $\mu_{d_3}$ | IC[a] | RIC[b] | RI[c] | IC | RIC | RI | IC | RIC | RI |
| 0.5 | 1 | 1 | 11.76 | 8.38 | 0 | 11.53 | 6.67 | 0.29 | 10.75 | 5.67 | 1.68 |
| 1 | 0.5 | 1 | 6.45 | 5.04 | 0.3 | 6.24 | 4.55 | 2.42 | 7.06 | 3.99 | 3.08 |
| 1 | 1 | 0.5 | 4.24 | 3.78 | 5.70 | 7.34 | 5.14 | 5.59 | 4.32 | 3.08 | 19.55 |

[a]: Investment cost (M$), [b]: Recovered investment cost (M$), [c]: Reliability index (MW)

Table 2. Final plans, $\boldsymbol{\mu_{d_1}=0.5}$, $\boldsymbol{\mu_{d_2}=1}$ and $\boldsymbol{\mu_{d_3}=1}$.

| Right-of-way | | Conventional capacity replacement = 0% | | | | Conventional capacity replacement = 40% | | | | Conventional capacity replacement = 80% | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| From | To | X[a] | Risk[b](%) | RIC[c](%) | AL[d] | X | Risk(%) | RIC(%) | AL | X | Risk(%) | RIC(%) | AL |
| 1 | 5 | 1 | 0 | 54 | No | 1 | 9 | 54 | No | 0 | - | - | - |
| 2 | 6 | 1 | 0 | 46 | No | 1 | 9 | 40 | No | 1 | 27 | 30 | No |
| 3 | 24 | 1 | 0 | 97 | Yes | 1 | 3 | 97 | Yes | 1 | 6 | 90 | Yes |
| 6 | 10 | 1 | 0 | 91 | Yes | 1 | 6 | 98 | Yes | 1 | 9 | 97 | Yes |
| 8 | 9 | 1 | 0 | 93 | Yes | 1 | 9 | 91 | Yes | 1 | 17 | 93 | No |
| 8 | 10 | 0 | - | - | - | 1 | 15 | 40 | No | 0 | - | - | - |
| 10 | 11 | 1 | 0 | 72 | No | 0 | - | - | - | 1 | 8 | 55 | No |
| 10 | 12 | 1 | 0 | 106 | Yes | 1 | 2 | 86 | No | 1 | 6 | 90 | Yes |
| 12 | 23 | 1 | 0 | 96 | Yes | 1 | 3 | 90 | Yes | 1 | 4 | 67 | No |
| 13 | 23 | 1 | 0 | 63 | No | 0 | - | - | - | 0 | - | - | - |
| 14 | 16 | 1 | 0 | 114 | Yes | 1 | 6 | 94 | Yes | 1 | 9 | 103 | Yes |
| 15 | 21 | 1 | 0 | 90 | Yes | 1 | 3 | 82 | No | 1 | 7 | 51 | No |
| 15 | 24 | 1 | 0 | 98 | Yes | 1 | 1 | 98 | Yes | 1 | 6 | 88 | No |
| 16 | 17 | 1 | 0 | 120 | Yes | 1 | 5 | 107 | Yes | 1 | 9 | 92 | Yes |
| 17 | 18 | 1 | 0 | 58 | No | 1 | 3 | 74 | No | 1 | 6 | 30 | No |
| 14 | 23 | 0 | - | - | - | 1 | 6 | 40 | No | 0 | - | - | - |

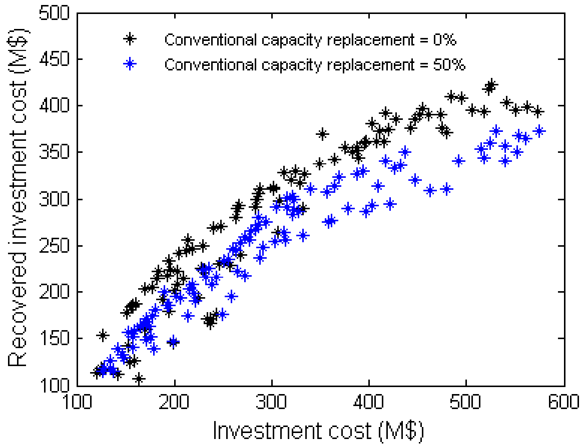
[a]: Installation status, [b]: Risk of investment, [c]: Recovered investment cost, [d]: Attractive line

$v_{ci}=3.5$, $v_r=16$, $v_{co}=25$. The actual data of wind speed at each site are employed to model the wind speed. The wind speeds are measured with time interval of 10 minutes for three years [39]. At these sites, scale parameter ($\alpha$) of wind speed is 9.4954, 13.8303 and 9.4954 m/s, and shape parameter is 1.6005, 1.5081 and 1.5543 m/s, respectively.

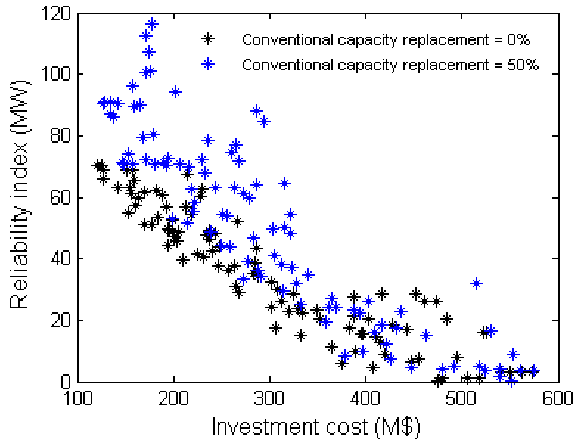
The algorithm of Fig. 1 is implemented for two states: without wind power generation, and with 50% conventional capacity replacement by wind generation type at the mentioned buses. The obtained trade-offs among TNEP objective functions are shown in Fig. 4. The impact of wind power generation on recovered investment cost and reliability index is obvious in this Fig. As depicted in Fig. 4(a), without wind power generation, the maximum value of recovered investment cost is 422 M$. However, when 50% of conventional capacity at buses 6, 25 and 18 is replaced by wind farms, the maximum recovered investment cost reduces to 372 M$. This reduction is about 11%. Also in Fig. 4(b), the reliability index increases when wind power capacity is installed. Supposing the available investment cost 300 M$ for expanding the transmission network, will led to reliability index of 29.72 and 20 MW with and without wind power capacity installation, respectively.

For the satisfaction levels $\mu_{d_1}=1$, $\mu_{d_2}=1$ and

$\mu_{d_3} = 1$ of the TNEP objective functions, the investment attractive lines are presented in Table 3. In which, the figure in the parentheses denotes number of attractive lines in the related right-of-way. With and without wind power generation, the number of attractive lines is respectively 42 and 50.




(a) Trade-off between investment cost and recovered investment cost.




(b) Trade-off between investment cost and reliability index.

Fig. 4. Trade-offs between the TNEP objectives in Iran 400 kV network, different percentages of conventional capacity replacement.

Table 3. Investment attractive lines in Iran 400 kV network.

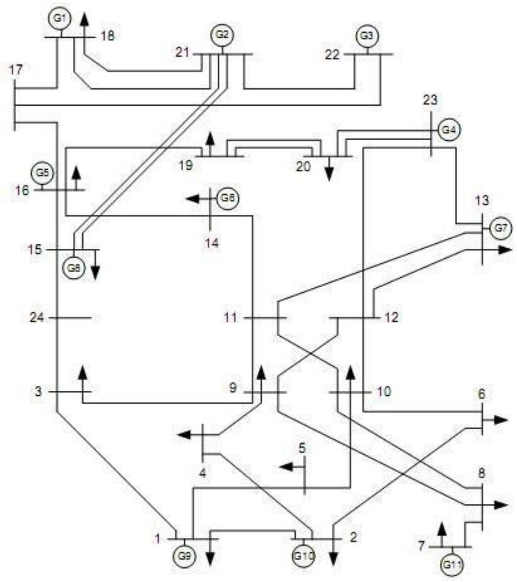
| **Conventional capacity replacement = 0%** | **Conventional capacity replacement = 50%** |
|---|---|
| 4-52(2), 5-28(2), 7-8, 7-12, 7-23(2), 7-24(2), 7-25(2), 9-11(2), 10-12, 13-17(2), 15-16, 21-22, 21-34, 22-23(2), 23-24(2), 23-29, 24-25(2), 24-26, 24-32, 26-29(2), 29-30, 32-34(2), 33-36, 33-37, 35-40, 36-37, 36-38(2), 37-39(2), 38-40, 39-40(2), 39-41(2), 40-41(2), 48-51 | 4-52(2), 7-8, 7-12, 7-23(2), 7-24(2), 7-25(2), 9-11(2), 10-12, 13-17(2), 14-15(2), 18-19, 21-22, 21-34, 22-23, 23-24(2), 23-29(2), 23-32, 27-28(2), 29-30, 30-31, 30-32, 32-34, 35-40, 36-37, 37-39(2), 39-40(2), 39-41(2), 40-41(2) |

## 4. CONCLUSION

The main purpose of this work was to investigate the impact of wind power generation on investment return in transmission network expansion planning. For this, some of the conventional generation capacities were replaced with the wind power plants. The simulation results confirm that high penetration of wind power generation reduces investment return and number of investment attractive lines. Also the large-scale wind farms increase power flow fluctuations in transmission lines and consequently increase investment risk. This is mainly due to the changeable and uncontrollable nature of the wind power generation and the possibility of ineffective utilization of new transmission lines. This discourages private investors for investing in transmission sections. A proper alternative to this problem is distributing wind power generation in smaller capacities all over the systems. This subject reduces power flow fluctuations and consequently reduces investment risk.

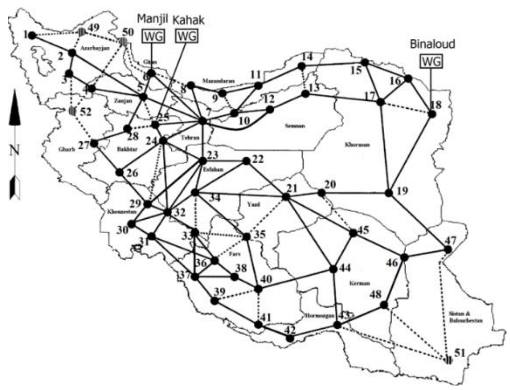
Appendix A.

Single-line diagram of IEEE 24-bus reliability test system (RTS).



Appendix B.

Single-line diagram of Iran 400 kV network.



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